ACTIVE / PASSIVE MICROWAVE REMOTE SENSING FOR SOIL MOISTURE RETRIEVAL THROUGH A GROWING SEASON

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ABSTRACT. An extensive field experiment was conducted from May-early October, 2002 at the heavily instrumented USDA-ARS OPE3 test site to acquire data needed to address active/passive microwave algorithm, modeling, and ground validation issues for accurate soil moisture retrieval. Vegetation cover consisted of a corn crop which was measured from planting through senescence and harvesting. Dual-polarized passive microwave data at 1.4 GHz were recorded continuously throughout the season using a new automated microwave radiometer deployed on an 18-m tower. These measurements were supplemented with weekly dual-frequency (1.6 and 4.75 GHz) quad-polarized radar backscatter data from a truck-mounted radar system. Ground measurements consisting of soil temperature (both physical and infrared), soil moisture (measured both gravimetrically and using portable and in situ probes), surface roughness, vegetation height and biomass, and vegetation geometry were routinely collected on a daily or weekly basis.

KEYWORDS. soil moisture, microwave radiometry, radar, moisture probes

INTRODUCTION

Remote sensing of surface soil moisture is not yet a truly operational technology, although the theory and methods [1, 2] to develop this important remote sensing resource are well established. A number of research studies using ground [3-7], aircraft [8, 9], and space-based sensors [10, 11] operating at low microwave frequencies (< 6 GHz) have shown that a surface layer of soil, on the order of 5 cm thick, can be accurately measured under a range of surface conditions. Although radars and radiometers are both sensitive to soil moisture to varying degrees and can be used independently to estimate soil moisture, the combination of simultaneous radar and radiometer data can enhance soil moisture retrievals, especially in the presence of dynamic vegetation [9].

Given the crucial role that soil moisture plays in most land surface processes, large-scale soil moisture mapping based on microwave remote sensing would be valuable in many different practical and theoretical applications, and a real potential exists for new space missions in the near future which will utilize simultaneous active/passive microwave measurements for global soil moisture retrieval [12]. To take full advantage of these opportunities, however, further development of joint active/passive microwave retrieval algorithms is necessary, especially over the full range of changing vegetation conditions typical of a normal growing season. At the same time, an assessment is required of the various instruments and methods available for ground validation of microwave-derived soil moisture measurements.

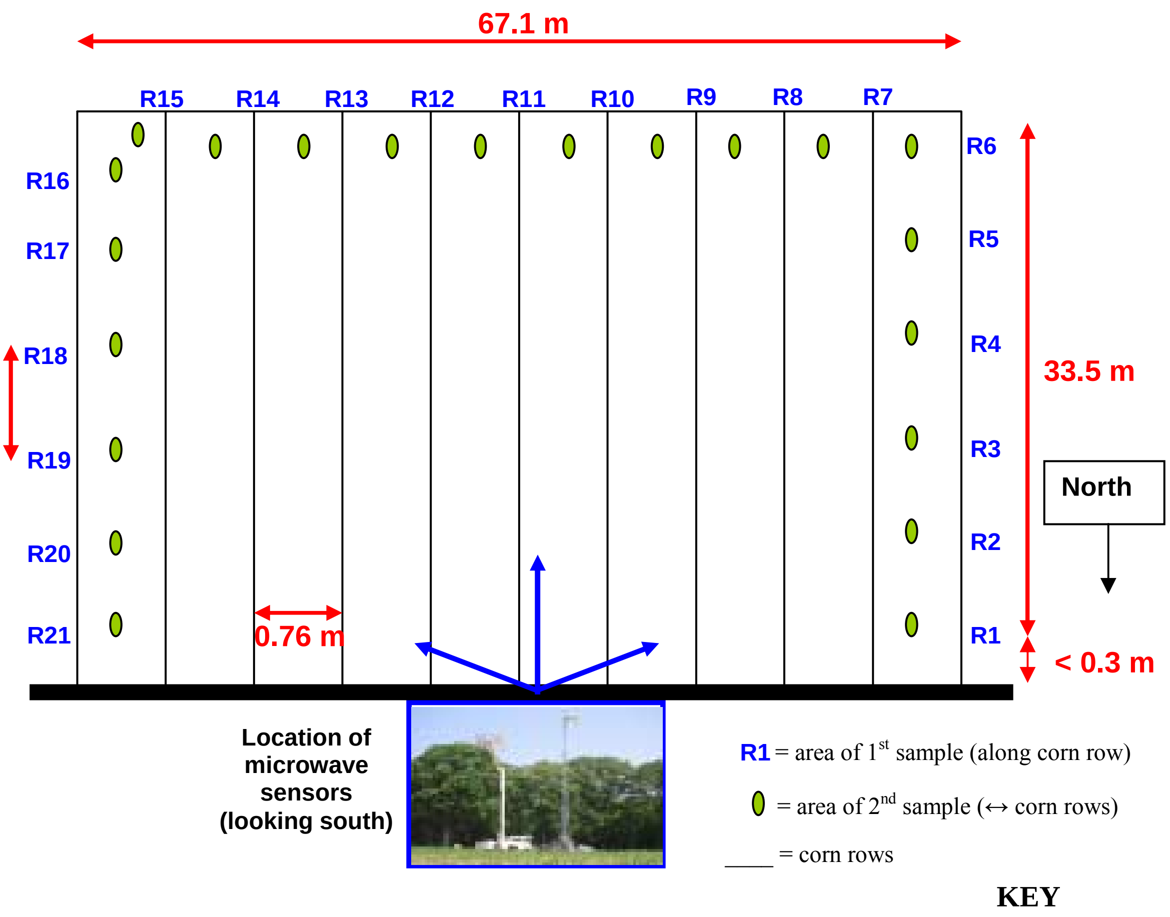
A field experiment was conducted from May-early October, 2002 at the heavily instrumented USDA-ARS (U.S. Dept. of Agriculture-Agricultural Research Service) OPE3 (Optimizing

Production Inputs for Economic and Environmental Enhancement) [13] test site in Beltsville, Maryland to acquire data needed to address these active/passive microwave algorithm, modeling, and ground validation issues for more accurate soil moisture retrieval. Extensive active and passive microwave data and ground soil moisture measurements were obtained on a daily or weekly basis throughout the growing season of a typical corn crop. Ongoing multifaceted analyses of the resulting comprehensive data set will be described which should provide improved soil moisture retrieval methodology under dynamic vegetation conditions and guidance for designing the most effective instrumentation for a soil moisture mission.

FIELD AND EXPERIMENT DESCRIPTION

OPE3 is an interdisciplinary research project started in 1998 to address major environmental and economic issues facing U.S. agriculture, including the fate of natural and man-made crop inputs, different farming methods, the impact of chemical inputs on adjacent lands and waterways, and the technology of gathering and analyzing spatial information on crops and soils for better management [13]. The site consists of four adjacent sub-watersheds with similar surface and sub-surface soil and water flow characteristics, about 4 ha (10 acres) each, which feed a wooded riparian wetland and first-order stream. For this summer's experiment, a tower-mounted 1.4 GHz radiometer (Lrad) and a truck-mounted dual-frequency (1.6 and 4.75 GHz) radar system were deployed on the northern edge of the northern-most sub-watershed known as Field A. Ground sampling locations were set up around the footprint of the microwave sensors as shown in Figure 1. The soil in this portion of the field is a sandy loam (silt 23.5%, sand 60.3%, clay 16.1%) with a measured bulk density of 1.253 g/cm^3.

Figure 1. Sampling Footprint for OPE3 Watershed A



Corn was planted on April 17, 2002, peak biomass was reached in late July, and the crop was harvested on October 2. Although drought conditions prevailed during the summer, the corn yield was near average. Figure 2 shows the corn at different times during the season.

May 6 **July 10** **August 21** **October 1**

Figure 2. OPE3 corn field A at different times during the growing season.

GROUND MEASURMENTS

To obtain ground measurements to compare with the data from the microwave sensors, twenty-one sampling locations were set up (Fig. 1) on three sides of the microwave footprint, which remained relatively undisturbed during the experiment. At each location gravimetric sampling of surface soil moisture in a 0-5 cm layer was conducted once a week to coincide with the simultaneous radar/radiometer measurements. These moisture data were supplemented at these and other times by nondestructive moisture measurements using portable theta probes and buried TDR probes (Fig. 3). In addition, USDA has installed a number of Sentek capacitance probes throughout the watershed at locations based on local texture, topography, and soil electrical conductivity properties to record profile moisture. Two such probes were a short distance outside the microwave footprint area. Vegetation biomass and geometry were also measured weekly along with surface and soil temperatures.

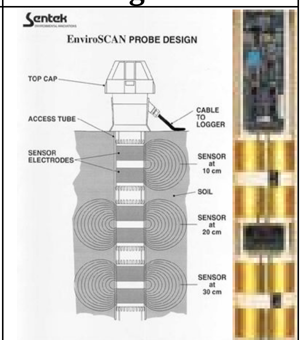
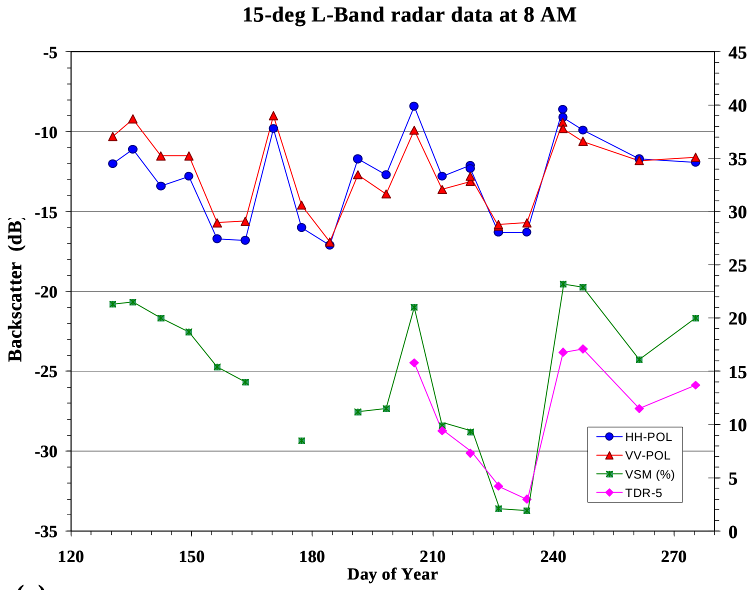
			
Theta probe	**Gravimetric soil moisture sampling**	**Profile moisture probe**	**Mesh board: soil roughness**
			
Weather station in fetch of field A	**Corn height measurement**	**Corn cutting for biomass sample**	**Sentek soil moisture probe**

Figure 3. A variety of ground truth measurements were collected during the experiment.

MICROWAVE MEASUREMENTS

Two microwave instruments were deployed at the OPE3 test site during the summer of 2002 to acquire a simultaneous active/passive microwave data set over the changing moisture and vegetation conditions of a dense crop during an entire growing season. The first sensor was a new NASA dual-polarized L band radiometer called Lrad operating at the protected passive sensing frequency of 1.4 GHz. During field operations Lrad was mounted on a portable 18 m tower (Fig. 4b), and was scheduled to acquire data every hour on a continuous basis throughout the summer at five incidence angles (25, 35, 45, 55, and 60 deg) and three azimuthal scan positions over the test field. At times, however, mechanical difficulties with the scanning system limited the Lrad data collection, particularly in the beginning of the summer.

The second microwave sensor deployed to OPE3 was the NASA / George Washington University (GWU) multifrequency (L, C, X band) quad-polarized (HH, VV, HV, VH) radar system mounted on a hydraulic boom truck with a 20 m boom (Fig. 4b). This radar is a very flexible and highly deployable system which has reliably provided calibrated radar data in soil moisture campaigns across the United States since the early 1990s (Chickasha, OK, Huntsville, AL, Boise, ID, and Beltsville, MD). These field campaigns, in turn, have provided the experimental data necessary to validate vegetation backscatter models developed by GWU and others. During field operations this past summer, the radar acquired sufficient independent samples during a data run by scanning the test field 120 degrees in azimuth from a boom height of 12.2 m at three different incidence angles (15, 35 and 55 deg).



(a)

(b)

Figure 4. (a) Example of time series radar data at 8 am compared to soil moisture data. (b) Microwave radar (left) and Lrad radiometer (right) deployed at OPE3.

Due to limited resources, radar data were collected one day a week throughout the summer at nominal times of 8 am, 10 am, 12 noon, and 2 pm, only at C and L band frequencies (4.75 and 1.6 GHz). Figure 4a shows like-polarized L band radar data taken at 8 am plotted with volumetric soil moisture as sampled gravimetrically (then converted to volumetric soil moisture by multiplying by the bulk density; shown as VSM on the plot) and as measured by TDR probes buried either horizontally or angled to represent a 5 cm soil depth at sampling sites R5, R11, and R18 (Fig. 1). The direct relationship between radar backscatter and surface soil moisture (as soil moisture increases so does radar backscatter) is obvious from the similarity of the pattern of the curves in Fig. 4a over the course of several wetting and drying cycles during the summer. Even though the TDR data are only available from mid-summer onward, their response is very close to that from gravimetric sampling; differences can be explained by the fact that the TDR probes are measuring a volume of soil centered on 5 cm whereas the gravimetric samples represent a surface layer from 0-5 cm.

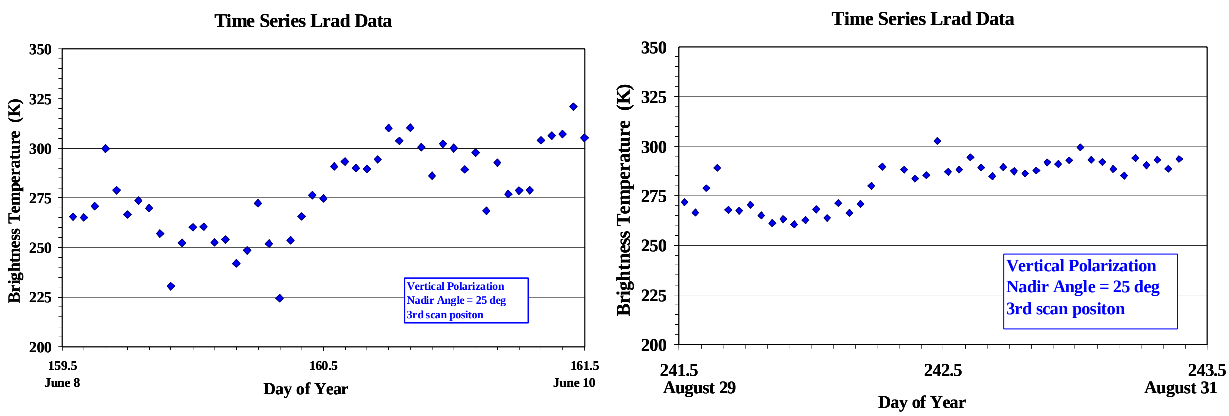


Figure 5. 48-hr Lrad data from a low biomass (early June) and wet high biomass (late August) period.

At the present time the calibration of the Lrad sensor is being finalized. Data in Figure 5 are based on a preliminary calibration and represent two 48-hour time series from a low biomass period in early June and a much wetter higher biomass period from late August. As expected, the increase in both soil moisture and overlying vegetation biomass serves to dampen the diurnal microwave response observed by Lrad.

COMBINED ACTIVE/PASSIVE MICROWAVE APPROACH

One method for using active/passive microwave data in combination to improve retrievals of surface soil moisture is to follow the procedure described by O'Neill et al. [9]. In this method radar data are used to validate the performance of a vegetation scattering model in which discrete scatter random media techniques are employed to calculate vegetation transmissivity and scattering; these parameters are then used in a soil moisture prediction algorithm based on a radiative transfer approach utilizing the passive microwave data [9, 14 and references therein]. The attenuation in the soil's microwave signal due to the presence of the overlying vegetation as calculated by the radar model is related to the transmissivity (γ) needed in the radiometer model by:

$$\text{Attenuation (dB)} = 10 \log_{10} (1/\gamma^2) \qquad (1)$$

The vegetation model requires as input information about the corn biomass, water content, and geometry (such as angle and size distributions for the corn leaves and stalks). This information was collected weekly during the experiment, and a portion of the data are presented in Figure 6. As expected, the canopy water constitutes the majority of the total canopy biomass for much of the growing season (Fig. 6a). In turn, the majority of the canopy water is located in the stalks (Fig. 6b). Given the vertical orientation of the corn stalks in the field, this means that the microwave response should show a polarization difference, with the stalks having more of an impact at vertical polarization, and thus the attenuation at vertical polarization should be higher. The large contribution of the corn cobs during the second half of the season is currently being incorporated into the vegetation scattering model.

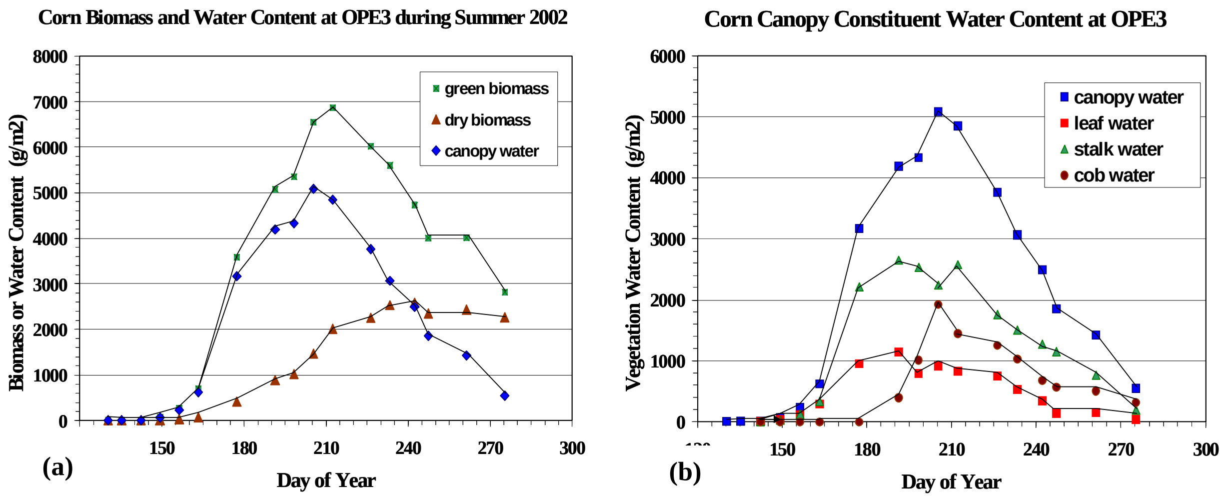


Figure 6. (a) Total corn canopy biomass as a function of corn water content and dry biomass during the season. (b) Canopy water by corn constituents.

Table 1. One Way Attenuation through Corn Canopy

			12-Jun-02			
		H			V	
Angle (deg)	**15**	**35**	**55**	**15**	**35**	**55**
Leaf Atten (dB)	0.24	0.29	0.40	0.24	0.30	0.47
Stem Atten (dB)	0.22	0.17	0.16	0.56	0.73	1.05
Total Atten (dB)	0.46	0.46	0.56	0.80	1.03	1.52
			24-Jul-02			
		H			V	
Angle (deg)	**15**	**35**	**55**	**15**	**35**	**55**
Leaf Atten (dB)	0.74	0.88	1.25	0.75	0.94	1.43
Stem Atten (dB)	2.30	2.81	3.45	4.20	6.27	10.10
Total Atten (dB)	3.04	3.69	4.70	4.95	7.21	11.53
			7-Aug-02			
		H			V	
Angle (deg)	**15**	**35**	**55**	**15**	**35**	**55**
Leaf Atten (dB)	0.69	0.81	1.16	0.69	0.87	1.33
Stem Atten (dB)	2.39	2.48	2.26	4.41	5.95	8.96
Total Atten (dB)	3.08	3.29	3.42	5.10	6.82	10.29
			30-Aug-02			
		H			V	
Angle (deg)	**15**	**35**	**55**	**15**	**35**	**55**
Leaf Atten (dB)	0.26	0.31	0.44	0.26	0.33	0.50
Stem Atten (dB)	0.60	0.47	0.48	0.75	2.06	5.21
Total Atten (dB)	0.86	0.78	0.92	1.01	2.39	5.71

Using the vegetation biomass and geometry collected during the experiment, the vegetation scattering model was used to produce estimates of attenuation at the radar incidence angles of 15°, 35°, and 55°. Results for four days are presented in Table 1 along with an illustration of how some of the corn geometry measurements were made against a gridded background. June 12 (day 163) is a low biomass day, July 24 (day 205) is near peak biomass, by August 7 (day 219) biomass is beginning to drop, and by August 30 (day 242) canopy water is beginning to drop below dry biomass in terms of its contribution to total canopy biomass. The estimated attenuation increases with incidence angle due to the greater path length through the canopy, is greater at vertical than horizontal polarization due to the erectophile nature of corn where the majority of crop water is contained in the vertical stalks, and closely tracks the biomass and canopy water curves shown in Figure 6. These values will be used to generate more accurate soil moisture retrievals once calibrated Lrad data become available.

SUMMARY

An extensive field experiment was conducted from May-early October, 2002 throughout an entire growing season of a corn crop from planting to harvesting to collect simultaneous active and passive microwave data for use in developing soil moisture retrieval algorithms which will retain their accuracy over widely changing vegetation conditions. Weekly L and C band radar data from a truck-mounted system were collected along with automated hourly L band radiometer data from a new tower-mounted sensor. Vegetation and soil moisture information acquired using several different manual and automated methods were compiled for comparison with the microwave measurements and for validation of microwave-derived geophysical products. The resulting experimental data set is relevant to new investigations in microwave remote sensing of soil moisture, to design of the most effective instrumentation for a soil moisture mission in space, to assessment of different portable and *in situ* ground soil moisture sensors, and to development of a truly synergistic active/passive microwave modeling approach for water and energy balance modeling.

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